Interpretation of the Helium Isotope Ratios Measured by IMAX

A.J. Davis[1], W. Menn[2], L.M. Barbier[3], E.R. Christian[3], R.L. Golden[4], M. Hof[2], K.E. Krombel[3], A.W. Labrador[1], R.A. Mewaldt[1], J.W. Mitchell[3], J.F. Ormes[3], I.L. Rasmussen[5], O. Reimer[2], S.M. Schindler[1], M. Simon[2], S.J. Stochaj[4], R.E. Streitmatter[3] and W.R. Webber[4]

[1] *California Institute of Technology, Pasadena, CA 91125, USA*
[2] *Universität Siegen, 57068 Siegen, Germany*
[3] *NASA/Goddard Space Flight Center, Greenbelt MD 20771, USA*
[4] *New Mexico State University, Las Cruces, NM 88003, USA*
[5] *Danish Space Research Institute, Lyngby, Denmark*

Abstract

We present here the IMAX ^{3}He/^{4}He ratios between 0.2 and 3.6 GeV/nucleon corrected to the top of the atmosphere, and a preliminary comparison with previous data and the predictions of a standard 'Leaky Box' model of CR transport in the galaxy. We find no evidence of an excess of ^{3}He over that predicted by the model, in the energy range studied.

1 Introduction

Accompanying papers (Reimer *et al.*, this conf.) present the ^{3}He/^{4}He and ^{2}H/^{1}H ratios measured by the IMAX instrument over the energy range 0.2 to 3.6 GeV/nucleon. These measurements of the secondaries of ^{4}He, along with recent measurements of antiprotons over a wide energy range by IMAX (Labrador *et al.*, Mitchell *et al.*, this conf.) and other balloon instruments, will result in a much better understanding of the origin and history of the light cosmic rays (CR) in the galaxy.

In this paper, we consider the implications of the ^{3}He/^{4}He ratios measured by IMAX. We correct for the effects of the instrument and atmospheric overburden on the ^{3}He/^{4}He ratio, and present the IMAX results corrected to the top of atmosphere (TOA). We then make a preliminary comparison of our results with previous measurements and with the predictions of a standard leaky box model of CR transport in the galaxy.

2 Instrument and Atmospheric Corrections

The most important corrections to the measured ratios account for the production of ^{3}He from spallation of ^{4}He above the IMAX tracking volume, and for fragmentation losses of both ^{3}He and ^{4}He in the instrument and residual atmosphere. Fragments of heavier CR also contribute in the atmosphere, but not significantly. Rigidity–dependent instrument acceptance corrections were also found to be negligible. There was a significant amount of material in the IMAX instrument above the tracking volume (12.24 g/cm^2 of aluminum, Teflon, scintillator and aerogel, not including 5.0 g/cm^2 of residual atmosphere), so an extensive survey of the literature was conducted to compile cross sections for both ^{3}He and ^{4}He. Figure 1 shows inelastic cross sections for ^{4}He beams with energy greater than 780 MeV/nucleon on various targets. These cross sections were parameterized using the formula

$$\sigma_{\text{inel}} = \pi(R_P + R_T)^2, \tag{1}$$

where $R_P = 1.075A_P^{0.355}$, $R_T = 1.075A_T^{0.355}$, and A_P and A_T are the projectile and target mass number, respectively. For ^{4}He, the substitution $R_{^4He} = 0.88R_{^3He}$ was

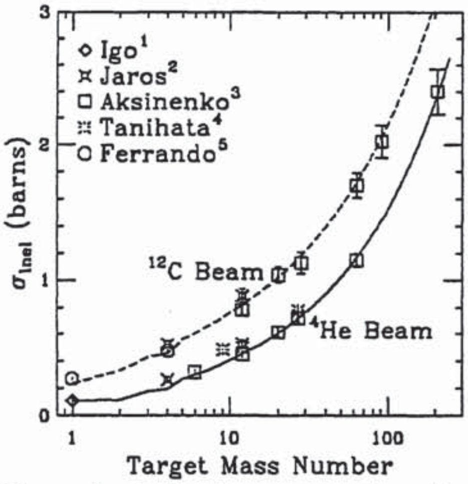

Figure 1. Inelastic cross sections for ^4He and ^{12}C with energy greater than 780MeV/nucleon in various targets.

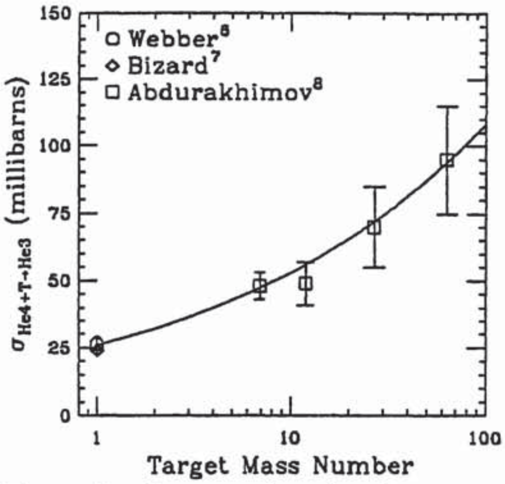

Figure 2. Cross sections for the production of ^3He from a ^4He beam in various targets.

made in Equation 1, since electron scattering measurements show the ^{4}He radius to be smaller than that of ^{3}He, and inelastic cross sections for ^{3}He in both carbon and aluminum targets are $\sim$9% greater than the ^{4}He cross sections[4]. This results in interaction lengths for ^{3}He and ^{4}He in air of 40 and 44 g/cm^2, respectively. Previous workers[9, 10] have apparently used an equal or longer pathlength for ^{3}He than for ^{4}He, which would result in an overcorrection of their isotope ratios to the TOA, if the cross section data we have considered is accurate. Figure 1 also shows cross sections for ^{12}C beams, and the curves in the figure indicate that our parameterization of the data is valid over a wide range of projectiles and targets.

Figure 2 shows cross sections for the production of ^{3}He due to ^{4}He spallation in various targets. These data were parameterized with a simple relation of the form $\sigma \sim A_T^{0.31}$, shown in the figure.

The cross section parameterizations described above were incorporated into a CR transport code for the atmospheric overburden and the IMAX instrument. This code was used to calculate correction factors to the TOA for the measured helium isotope ratios. The atmosphere and instrument materials were divided into thin slabs, and CR spectra were propagated through the slabs, taking into account energy losses, fragmentation losses, and additions due to the fragmentation of heavier species. Inputs to the code were model TOA ^{3}He and ^{4}He spectra, which were changed iteratively until the ratios of the propagated spectra matched the measured helium isotope ratios, under the additional constraint that the sum of the two spectra matched the measured total helium spectrum. When a good match was achieved, corrections to the IMAX ratios were calculated by comparing the TOA spectra input to the code and the propagated output spectra.

The transport code was also used to calculate the sensitivity of the corrections to the uncertainties in the cross sections. The code was run a large number of times, each time randomly perturbing the cross sections within the 10% estimated errors. Each run resulted in slightly different corrected TOA isotope ratios. The standard deviation of the distribution of these different corrections was 0.007, independent of energy, and was added in quadrature to the statistical errors of the isotope ratios. An additional factor of 0.006 was added in quadrature to reflect our uncertainty in the efficiency with which the IMAX detectors veto ^{4}He interactions which produce ^{3}He.

Table 1 lists the measured ^{3}He/^{4}He ratios, and the ratios corrected to TOA. The

Instrument		Top of Atmosphere	
Energy (MeV/nuc.)	^{3}He/^{4}He Ratio	Energy (MeV/nuc.)	^{3}He/^{4}He Ratio
200–400	0.139 ± 0.006	245–445	0.120 ± 0.011
400–600	0.153 ± 0.006	436–636	0.134 ± 0.011
600–800	0.168 ± 0.007	632–832	0.148 ± 0.012
800–1000	0.199 ± 0.009	830–1030	0.177 ± 0.013
1000–1200	0.203 ± 0.009	1029–1229	0.183 ± 0.013
1200–1400	0.205 ± 0.011	1228–1428	0.187 ± 0.014
1400–1600	0.213 ± 0.012	1428–1628	0.195 ± 0.015
1600–1800	0.203 ± 0.013	1627–1827	0.186 ± 0.016
2550–3020	0.245 ± 0.017	2576–3046	0.226 ± 0.019
3020–3660	0.218 ± 0.017	3046–3686	0.201 ± 0.019

Table 1. The IMAX ^{3}He/^{4}He ratios, and the ratios corrected to TOA.

correction factors varied between 0.86 and 0.92, rising with energy.

3 Discussion and Conclusions

To compare our results with theoretical models, the solar modulation level during the flight must be determined. The best measures of the solar modulation level are the IMAX proton and helium spectra, however our determination of these spectra is not yet complete, so the solar modulation parameter Φ was estimated from IMP–8[11] and neutron monitor data. We find that $\Phi = 750 \pm 50$MV during the flight.

We present here the results of a leaky box CR transport model which uses a rigidity–dependent path length distribution $\lambda_e = 31.6\beta R^{-0.6}$ for $R > 4.7$GV, and $\lambda_e = 12.4\beta$ for $R < 4.7$GV. The source spectrum used was a power–law in momentum with a spectral index of 2.2[12]. These parameters fit the the Englemann *et al.*[13] B/C ratio. Figure 3 shows the IMAX ^{3}He/^{4}He ratios with the results of the model, modulated to $\Phi = 750$MV, superimposed. The model is consistent with the IMAX ratios above 800MeV/nucleon, but predicts ratios about 15% greater at lower energies. Since we have not yet fit the model to the measured IMAX helium spectrum, we

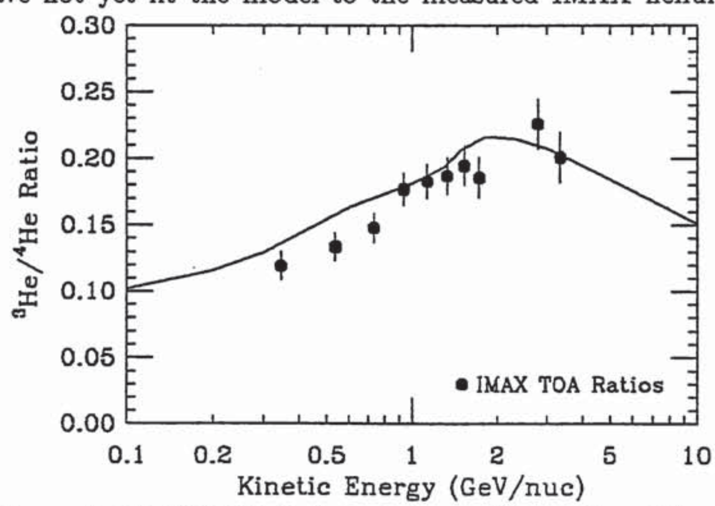

Figure 3. IMAX TOA helium isotope ratios and model results.

simply note that our current results indicate no excess of ^{3}He over that predicted by a standard leaky box model of helium transport in the galaxy.

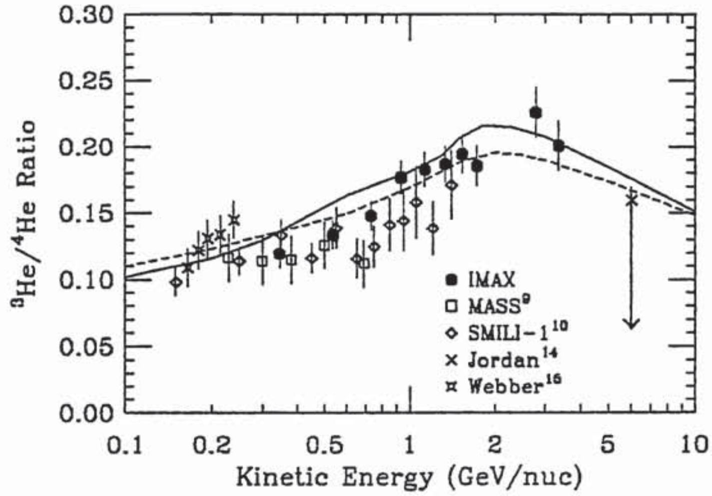

Figure 4. IMAX TOA helium isotope ratios compared with the results of other balloon experiments. The solid curve shows the transport model results modulated to $\Phi = 750MV$. The dashed curve shows the model modulated to 1200MV.

calc. af cor Webbe have d

In Figure 4 we compare our results with those of some other balloon experiments. Our ratios are higher than the SMILI–1 and MASS ratios, which is to be expected since both these experiments flew during high solar modulation levels. However, the leaky box transport model results, modulated to 1200MV, are not consistent with the SMILI–1 and MASS data. Alternative pathlength distributions need to be considered in the transport model, and the cross sections used in the model, as well as those used to correct previous balloon data to the TOA, may need to be reevaluated.

This work supported by NASA under grant NAGW–1919 and other grants.

References

[1] Igo, G.J., *et al.*, Nucl. Phys., **B3** (1967), 181
[2] Jaros, J., *et al.*, Phys. Rev. C, **18** (1978), 2273
[3] Aksinenko, V.D., Nucl. Phys., **A348** (1980), 518
[4] Tanihata, I, *et al.*, Phys. Lett., **160B** (1985), 380
[5] Ferrando, P., *et al.*, Phys. Rev. C, **37** (1988), 1490
[6] Webber, W.R., AIP Conf. Proc. 203, ed. W.V. Jones, F.J. Kerr and J.F. Ormes (New York:AIP), 294
[7] Bizard, G., *et al.*, Nucl. Phys., **A285** (1977), 461
[8] Abdurakhimov, A.Kh., Nucl. Phys., **A362** (1981), 376
[9] Webber, W.R. *et al.*, Ap.J. **380** (1991), 230
[10] Beatty, J.J. *et al.*, Ap.J. **413** (1993), 268
[11] McGuire, B., Schuster, F. and McDonald, F., private communication.
[12] Gupta, M. and Webber, W.R, Ap.J. **340** (1989), 1224
[13] Englemann, J.J., *et al.*, A&A **233** (1990), 96
[14] Jordan, S.P. and Meyer, P., Phys. Rev. Lett., **53** (1984), 505, reanalysed by Webber, W.R., *et al.*, Ap.J. **312** (1987), 178
[15] Webber, W.R. and Yushak, S.M., Ap.J. **275** (1983), 391